



Effect of Operational Parameters on Drying Rate and Energy Consumption of Epoxy-Based Coating Powder in a Fluidized Bed Dryer System

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Abstract

In this work, the effect of inlet air temperature and volume flow rate is studied on the moisture content of epoxy-based coating powder and energy consumption of a fluidized bed dryer system. The inlet air temperature range was determined to be 45-60°C based on the glass transition temperature of epoxy-based coating powder. The results showed that by increasing the inlet air temperature in the fluidized bed dryer, the drying rate of the samples increased, where the highest drying rate was obtained at 60°C. In the temperature range of 55 to 60°C, an increase in inlet air volume flow rate led to an increase in the drying rate. An increase in the inlet air temperature significantly led to an increase in the energy consumption for drying the samples. The drying rate of the samples did not have a constant trend because of an increase in the inlet air volume flow rate. The results showed the drying rate of samples increased by an increase in volume flow rate from 1.0 to 1.4m³/s, and its value decreased from 1.4 to 1.6m³/s. However, the amount of energy consumed by the dried samples increases with the increase in the inlet air volume flow rate. The results of this study can be effective in achieving the optimal amount for drying the powder and reaching the optimum value of less than 2% by spending the minimum amount of necessary energy and the maximum drying rate of the powder.

Keywords: Fluidized bed dryer; Drying rate; Energy consumption; Optimization of parameters; Epoxy-Based coating powder.

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1. Introduction

Epoxy resins are materials that are mainly used as thermoplastic such as adhesives, corrosion resistant materials and composites [1-3]. Epoxy-based powder shows high reactivity, which is twice stronger than concrete in terms of mechanical strength and is completely resistant to water permeability [4]. Epoxy resins are generally a glassy material at room temperature. It is difficult to determine the type of polymer network structure due to their impenetrability at high temperatures

and their insolubility in organic solvents [5,6]. Maguire *et al.* (2024) reported a low drying rate for epoxy-based coating powder (1.5°C/min), where the melting temperature of a sample should not be lower than 120°C as found by using a calorimetric analysis [7]. However, the degradation of epoxy-based coating powder generally occurs in the temperature range of 190-200°C within 15 min. Using the post-drying stage is known as an important role in reducing the degradation temperature of powder. In this method, a mixture of the coating powder dried at 60°C is combined

with the wet sample and the final mixture is dried in a fluidized bed dryer [8].

The drying process of powder is taken place in a fixed or fluidized bed dryer. Fixed beds have disadvantages, such as a high possibility of powder agglomeration during drying and non-uniformity of humidity (solvent content) of powder. In contrast, fluidized bed dryers are suitable for processing and fluidization of a wide range of materials, from granules to powder [8,9]. The size, shape, Geldart's classification cohesive and nature of particles can significantly influence their drying rate in a fluidized bed dryer. The retention time of particles, air flow velocity and static bed height can also affect the particle size distribution and moisture content of powder.

Fluidized bed dryers have been widely used in drying minerals, chemicals, ceramics, waste products, and polymeric material [7-9]. In addition, fluidized bed dryer has disadvantages such as pressure drop across the bed length and high energy consumption due to the fluidization of the particles. Therefore, the performance of the fluidized bed dryers and its energy consumption and the effect of operating parameters on the mentioned parameters are essential from engineering aspects.

Kalbasi et al. (2010) modeled the behavior of alumina slurry in a spray dryer based on the simultaneous solution of the equations of mass transfer, heat transfer and momentum transfer [9]. They found that the input parameters of the dryer have an effect on the characteristics of the powder [9]. They also showed that the changes in the moisture content of samples increase along the bed length, which is attributed to the mass (moisture) transfer of the solvent droplets from the liquid phase to the gas phase. It was also shown that the trend of gas temperature decreased across the bed length, which is attributed to the supply of energy needed to evaporate moisture droplets from the gas flow.

At the beginning of the drying process, the residual solvent evaporates from the surface of particles, while the heat is transferred from the bed surface to the center of the droplets. Therefore, there is no significant change in the moisture content of the droplets caused by excess heat, which leads to heat loss and high energy consumption. On the other hand, the high-volume flow rate of the inlet air led to the air leaving the fluidized bed dryers without being saturated with moisture and high energy losses. Thus, it is suggested to combine the fluidized bed dryer with the fixed bed dryer, so that the fixed bed is located in the continuation of the air exit from the fluidized

bed dryer. Varte Parvar et al. (2012) analyzed the energy parameters affecting energy consumption, and the ratio of energy consumption in a combined drying process [10]. The results showed that the energy consumption is independent of the types of drying methods. An increase in the static bed height affects the energy consumption of the upper tray. The highest energy consumption was obtained at a temperature of 70°C the height of the fixed bed. In addition, the highest ratio of energy consumption was obtained at a temperature of 50°C. Taghavivand et al. (2010) studied the energy analysis and drying rate of carrots by a change in the particle size, bed thickness, and air flow rate during drying in a fluidized bed dryer [11]. The results showed that the energy consumption for drying a certain mass of particles increases by increasing the air velocity and the thickness of the bed, as well as reducing the particle size [11].

Firouzi et al. (2014) showed that the inlet air temperature and the inlet air volume flow rate are effective on the drying time, the drying of residual solvent, and the energy consumed by solid materials in a fixed bed dryer [12]. They found that the drying time of samples decreases by an increase in the inlet air volume flow rate, while drying time increases by an increase in the inlet air temperature. Also, the amount of energy consumed per weight of particles decreases by an increase in the inlet air temperature and air velocity [12]. Abbasi Fard et al. (2013) showed that in a rotary dryer, apart from the slope of the dryer chamber and the speed of rotation of the particles inside it, the humidity and temperature of the incoming air have the greatest effect on the humidity of the output of the product [13]. Rousselet et al. (2016) studied the effect of operational parameters on the performance and energy consumption of a rotary dryer [14]. They showed that the efficiency and energy consumption of the dryer is a function of the initial humidity of the particles and the mass transfer mechanism of the particles determines the drying rate of the particles. Khanali et al. (2017) showed an increase in the inlet gas temperature of the fluidized bed dryer led to a decrease in the moisture content of corn [15]. They also reported an increase in the mass of the input material, leading to an increase in the moisture of solid materials [15].

High temperature fluidized bed is usually suggested as one of the suitable methods for drying of wet granular materials in the industrial-scale. Based on performance, optimization of parameters in each 150kg in each batch can lead to energy consumption of about 18.5kWh, which led to an annual energy storage equivalent to 3,700kWh. Only 55-60% of the heat provided by a fluidized

bed dryer is applied to dry the moisture (residual solvent) of the samples, and the rest of the produced heat is lost as a waste through the outlet of the dryer. In terms of energy consumption, the efficiency of fluidized bed dryers is ~50% or less, thus the optimization of parameters helps us to save consumption energy during drying of wet materials. Therefore, the need to simultaneously examine the operation of a fluidized bed dryer and the energy consumed to dry a specific mass of wet material is an importance to study from an industrial point of view.

A review of the studies shows that a lot of research has been carried out on the use of fluid bed dryers in drying chemical and polymer materials. However, no comprehensive research has been reported on the drying rate of epoxy-based coating powder, considering thermal parameters and energy consumption per mass of dried powder. In this research, the effect of operating parameters on the performance and energy consumption of a fluid bed dryer in drying epoxy-based coating powder in a fluidized bed dryer (fluidized sample) and a thermal oven (control sample) were compared. The inlet air temperature was considered at four levels of 45, 50, 55, and 60°C and the inlet air volume flow rate was considered at three levels of 1.0, 1.2, 1.4, and 1.6m³/s. The drying performance of the two methods was compared by determining the amount of residual solvent content (changes in the weight of the two samples) and the amount of energy consumed by each of the methods (fluidized and control samples). Finally, the optimal operating conditions for drying the resulting epoxy-based coating powder were determined and presented in this study.

2. Experimental Procedure, Equipments and Materials

2-1. Materials

To prepare the epoxy-based coating powder, epoxy resin 505-ML (density and viscosity are 1.54g/cm³ and 1450cP, respectively) and HA-11 hardener were used from the products of the Mokarar engineering company. No solvents or non-reactive agents are used in the epoxy resin, in which the polymer structure of the product remains stable after the reaction and does not undergo any weight changes.

2-2. Materials Preparation

The samples were divided into two parts. The first part for final drying was placed in a thermal oven

at temperature ranges of 45-60°C for 2h (control sample). In the second part, the sample was placed in a fluidized bed dryer (fluidized sample). The drying of samples was performed under different operating conditions in a fluid bed dryer.

2-3. Fluidized Bed Dryer

Fig. 1 shows the fluidized bed dryer system and its components. The drying chamber is made of Pyrex glass with cylindrical coordinates with a diameter of 7.8cm and a length of 18cm. The electric heater included thermal elements with a thermal power of 3000W and could provide hot air up to a temperature of 200°C. The temperature controller (model XH-W3001) was used to measure and control the temperature, which could keep the temperature of the incoming air at a desired value with an accuracy of ±1°C. To perform drying experiments in fluidized bed dryer, the inlet air temperature was considered at four levels of 45, 50, 55 and 60°C and the volume rate of the inlet air at three levels was 0.16, 0.14 and 0.12m³/s. All experiments were repeated three times to obtain reliable results. The drying process continued until the complete removal of the solvent from the epoxy base coating powder.

2-4. Weighing Analysis

Before and after drying, the weight of the samples was recorded at a certain time. The weight of the samples was done on a precise digital scale. The accuracy of the digital scale for weighing was approximately 1%. The moisture content of the samples at different times was calculated using the following relationship:

$$M_d = \frac{W_w - W_d}{W_d} \quad (1)$$

where M_d is the remaining solvent content, W_w is the weight of the wet sample, and W_d is the weight of the completely dry sample in grams. The drying rate of the samples was calculated by the data obtained from the percentage reduction of the solvent content of the samples per unit of time [16].

$$R = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (2)$$

where R is the drying rate (Solvent content reduction per hour %), $M_{t+\Delta t}$ is the remaining solvent content in the sample at the moment $t+\Delta t$ (%), M_t is the remaining solvent content in the samples at the t (%), and Δt is the time interval during reduction of the residual solvent content in the samples in terms of hour.

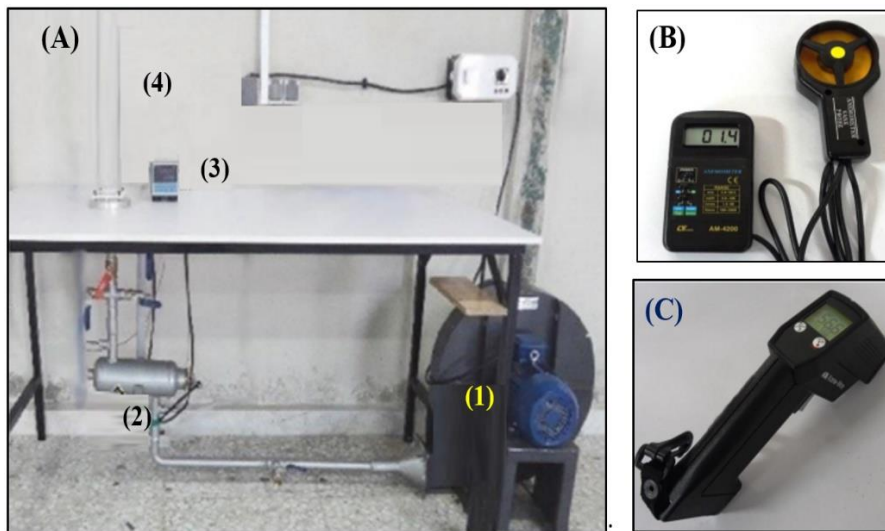


Fig. 1. Fluidized bed dryer system and its accessories (A: fluidized bed dryer (1: compressor, 2: electrical chamber, 3: temperature controller, 4: drying chamber), B: Anemometer, C: Thermometer)

2-5. Energy Consumption Calculation

The thermal energy required to dry the samples was calculated using the total applied thermal power (E) during the drying time for each step [17]:

$$E = \frac{Q(C_{pa} + C_{pv} h_a)(T_{in} - T_a)}{V_h} \quad (3)$$

where Q is the inlet air volume flow rate (m^3/s), C_{pa} and C_{pv} are the specific heat capacity of air and steam ($\text{J}/\text{kg}^\circ\text{C}$), respectively, h_a is the absolute air humidity of dry air (kg), T_{in} and T_a are the temperature of inlet air and ambient air, respectively ($^\circ\text{C}$), and V_h is the specific volume of air (m^3/kg).

To determine the total energy consumption of the fluidized bed dryer in each run, the required time was accounted for the working of heaters and centrifugal blower fan. The energy consumption of heaters was measured at different conditions (according to the inlet air volume flow rate and temperature) using the Equation 4. Then, the resulting data was added to the energy consumption of the blower fan to obtain the total energy consumption of the system:

$$E = P \times t \quad (4)$$

where E is the energy consumption (kWh), P is the applied thermal power (kW), t is the required drying time for each step of the drying (h). The total applied thermal power (P) is determined by the following:

$$P = Q \times \rho_{air} \times C_p \times \Delta t \quad (5)$$

where Q is the inlet air volume flow rate (m^3/s), ρ_{air} is the air density (kg/m^3), C_p is the specific heat capacity of the air ($\text{kJ}/\text{kg}^\circ\text{C}$), and Δt is the difference between the inlet temperature and the ambient temperature.

3. Results and Discussion

3-1. Effect of Temperature on Drying Rate of Samples

Fig. 2 shows the variation of the moisture content of the samples versus time at different inlet air temperatures. The inlet air volume flow rate was considered constant and equal to $1.6\text{m}^3/\text{s}$. The moisture content of powder decreases with increasing time. An increase in inlet air temperature led to an increase in the drying rate of powder, and the trend of decreasing humidity changes continues until reaching its equilibrium value. An achieved to reach the equilibrium humidity of the powder to less than 2% is considered as a critical point to obtain a desired sample, which is observed in the temperature range of $55\text{-}60^\circ\text{C}$ for 10min. In the first 2min, the trend of moisture content changes with time and is almost constant (as characterized by the first step of drying). This result shows the surface humidity of the powder is so high in the beginning of drying process that the temperature cannot dry the surface of the particles, which indicates there is no resistance to the mass transfer of moisture content from inside the particles to its surface. Therefore, an increase in the inlet air temperature is not effective on the drying rate of powder at the beginning of drying process.

In the period of 3-9min, a maximum decrease in moisture content of samples is observed, which is characterized by the second step of drying. This issue can be attributed to a significant decrease in surface humidity of samples, which led to an increase in the gradient of mass transfer of solvent from inside the samples to its surface. In the second step, the effect of mass transfer resistance and the

diffusion phenomenon of solvent from the inside of the particle to its surface decreases by inlet air temperature. Therefore, the change of moisture content of sample with time shows a decreasing trend at 60°C. In the period of 9-12min (third step), the moisture content variation of the powder takes a downward trend with time, which is named as the third step of drying. This result can be attributed to the reduction of the solvent content in the internal structure of the powder, which is difficult to separate from it and reaches to its surface through the interlayer diffusion mechanism.

3-2. The Effect of Temperature on the Energy Consumption of System

Fig. 3 shows the variation in the energy consumption versus the drying time of the samples at different temperatures. The inlet air volume flow rate was considered constant and equal to $1.6\text{m}^3/\text{s}$. The trend of reducing energy consumption over time is similar to the moisture content-time curve. It can be seen that the required energy to dry the sample decreases with increasing time. In addition, the amount of energy required to reduce the moisture content of a sample increases with an increase in inlet air temperature. In the first step of drying, the consumed energy is almost constant, and its variations are minor. This shows that the surface moisture of the particles is so high that the temperature of the samples is not allowed to dry. Therefore, high energy is needed to reduce the moisture content of samples. A maximum change in energy consumption with time is reported in the second step of drying. This result can be attributed to an increase of the thermal gradient from the

outside of the particles to their inside. Therefore, the energy consumption increases to increase the drying rate of samples. In the third step of drying, the energy consumption decreases with time, which can be attributed to the reduction of the temperature gradient inside the powder compared to its surface. At this step, the trend of energy consumption changes is fixed with drying time. At times longer than 12min, the energy consumption does not lead to a decrease in the moisture content of the particles, and a loss of thermal energy is observed in the energy-time curve.

Fig. 4 shows the variation in energy consumption of the system versus the drying rate of samples at different temperatures. An increase in the drying rate of the samples is caused by an increase in the amount of energy consumption. The optimal state occurs when the highest drying rate of particles is associated with the lowest amount of energy consumption. An increase in inlet air temperature led to an increase in the drying rate of samples and an increase in energy consumption. The trend of changes in the energy consumption-drying rate curve is similar to the variation of the drying curve of the sample (Fig. 2). The changes in energy consumption in the first and third steps of the drying curve are gradual, while the most changes are seen in the second step. According to the results, the highest and lowest amounts of energy consumption are related to temperatures of 60 and 45°C, respectively. At the temperature of 55°C, the highest drying rate of the samples is observed against the lowest amount of energy consumption. Therefore, it can be found that the inlet air temperature plays a vital role in the secondary step of samples drying.

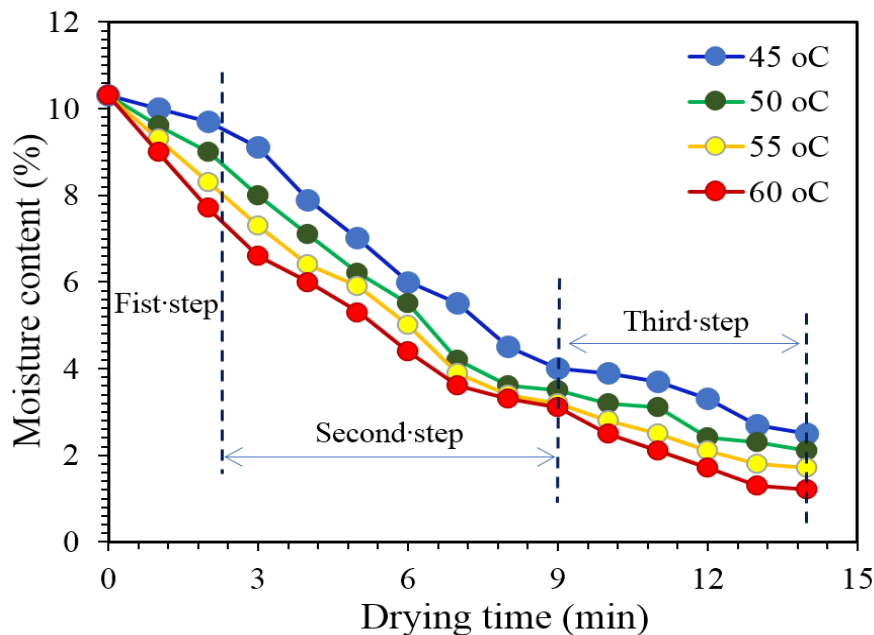


Fig. 2. The variation of the moisture content of the samples versus time at different inlet air temperatures [The inlet air volume flow rate was $1.6\text{m}^3/\text{s}$].

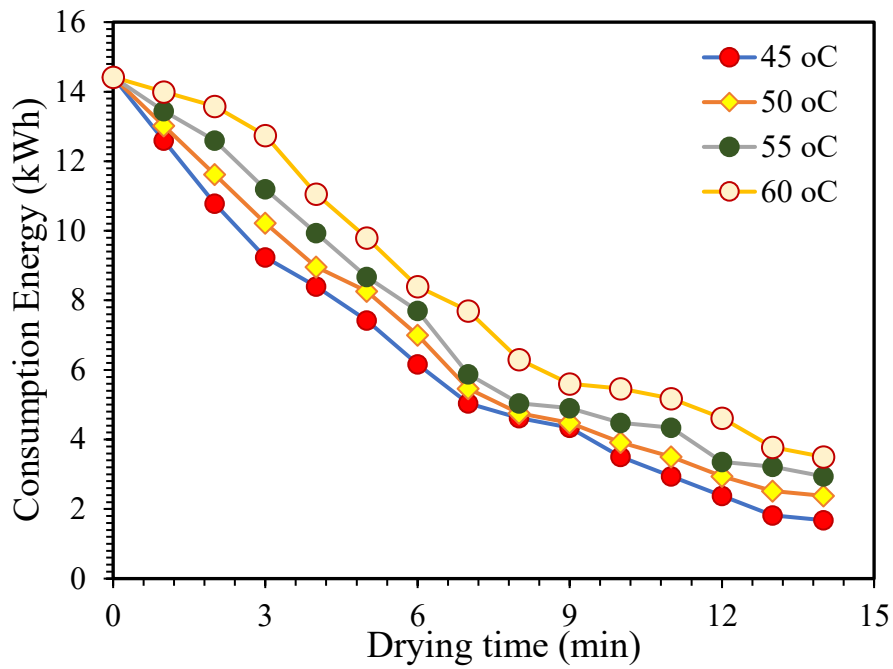


Fig. 3. The variation of the energy consumption versus drying time of the samples at different temperatures

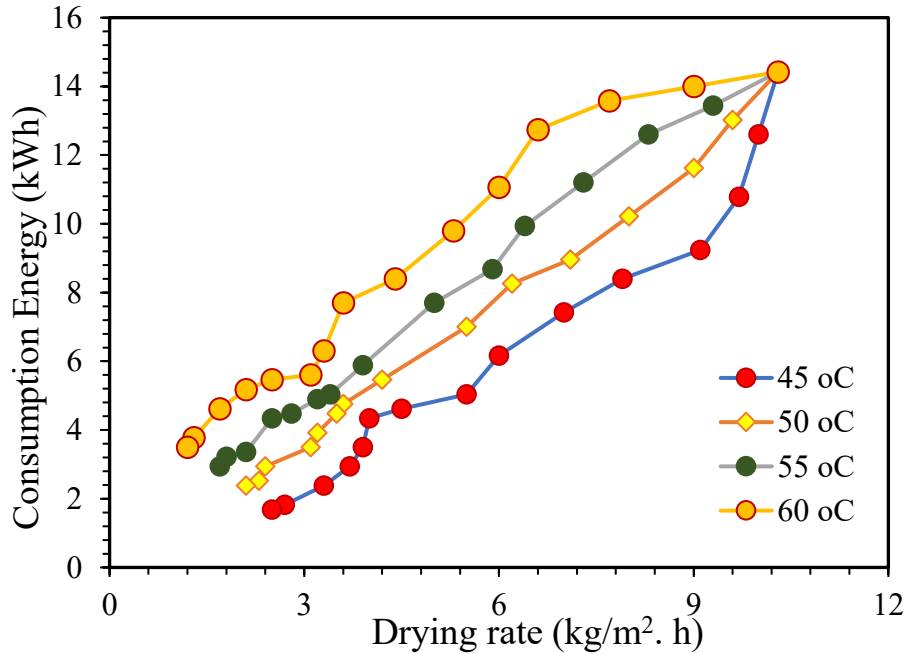


Fig. 4. The variation of energy consumption of system versus drying rate of samples at different temperatures.

3-3. The Effect of Air Volume Flow Rate on the Rate of Samples

Fig. 5 shows the variation of the moisture content of the samples with time at different inlet air volume flow rates. The inlet air temperature is considered at 55°C. The results showed that the variations of the moisture content of samples does not follow a constant trend with a change in the inlet air volume flow rate. An increase in the inlet air volume flow rate from 1.0 to 1.2m³/s led to a decrease in the moisture content of samples, and then the decreasing trend is obtained until the

amount of moisture content reaches from 1.4 to 1.6m³/s and drying curve reaches the equilibrium state. Therefore, the lowest value of moisture content of the samples was observed at the inlet air volume flow rate of 1.4m³/s. In this condition, the moisture content of samples reach the equilibrium state ($\geq 2\%$). In the first step of drying, the inlet air volume flow rate did not have a significant effect on the moisture content of the samples. The surface moisture of the samples was effective on the drying rate of the samples, where the drying rate of samples was controlled by the surface moisture. In the two and third steps of the drying curve, the

effect of the inlet air volume flow rate on the moisture content of the sample become more obvious than in the first step.

The maximum effect of the inlet air volume flow rate on the moisture content of the samples was determined in the second step of the drying at $1.4\text{m}^3/\text{s}$. The high velocity of the inlet air led to an increase in the air leaving the bed without being saturated with moisture and without affecting the moisture content of the samples. An increase in the inlet air volume flow rate led to an increase in the collision of particles, and due to the impact of interparticle forces, the particles stick to each other to form simple- or complex-agglomerates [16]. Therefore, increasing the inlet air volume flow rate led to an increase in the average diameter of the particles in the fluidized bed. An increase in the size of the particles reduces the drying rate of particles. Therefore, the inlet air volume flow rate

is effective in the drying rate of samples. However, an increase in the air velocity led to an increase in the possibility of microparticles from the dryer chamber.

3-4. The effect of inlet air volume flow rate on the energy consumption

Fig. 6 shows the variation in the energy consumption of the system versus the drying time of samples at different inlet air volume flow rates. Contrary to the variation of moisture content of samples with time at different inlet air volume flow rates (Fig. 5), an increase in the inlet air volume flow rate led to a decrease in the required energy of system to reduce the moisture content of the samples. The highest value of energy consumption occurs in the first and second steps of drying process.

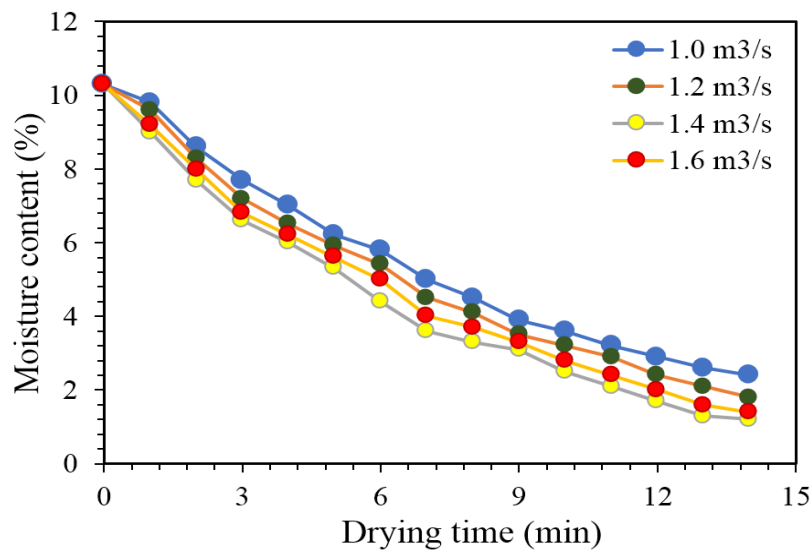


Fig. 5. The variation of the moisture content of the samples with time at different inlet air volume flow rates

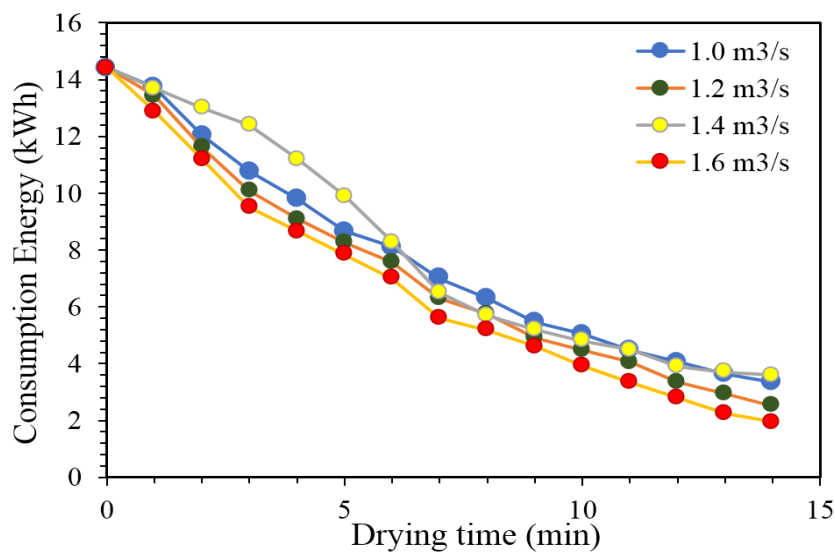


Fig. 6. The variation of the energy consumption of the system versus drying time of samples at different inlet air volume flow rates

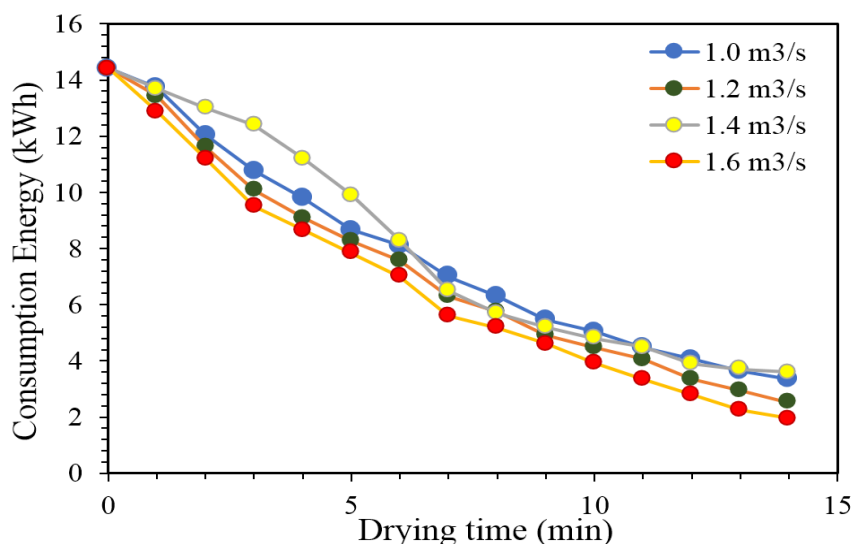


Fig. 7. The variation of the energy consumption versus the drying rate of the samples at different inlet air volume flow rates

In the first step of the drying, the consumed energy has a relatively constant trend with time, while minor changes are found in the results. In the second step of drying, the maximum changes in energy consumption with time was determined, which arose from the high drying rate of the samples. In the third step of the drying, the energy consumption decreases with time, where the values of energy consumption of the system and moisture content of samples are almost close to each other. This result can be attributed to the reduction of the temperature gradient inside the powder compared to its surface, which mainly occurs in the third step of drying.

At drying times of more than 12 min, the energy consumption does not lead to a decrease in the moisture content of the particles, while a loss of thermal energy is evident in the results. However, fluidized bed dryers have the highest amount of energy loss due to fluidization of particles and high transfer of gas phase [7,14,16], optimizing the inlet air volume flow rate has a significant effect on reducing the amount of energy consumption of the system per specific mass of sample.

Fig. 7 shows the variation in the energy consumption versus the drying rate of the samples at different inlet air volume flow rates. The results showed an increase in the drying rate of the samples that led to an increase in the amount of energy consumed by the particles. The optimal state occurs when the highest drying rate of particles is associated with the lowest amount of energy consumption. As obtained previously, an increase in the inlet air temperature led to an increase in the drying rate of samples and an increase in energy consumption [18]. The variation of energy consumption with drying rate is similar

to the mentioned steps of particle drying (Fig. 2). The changes in energy consumption in the first and third stages of drying are gradual, while in the second stage, a gradual change is observed in the corresponding curve. According to Fig. 7, the highest and lowest amount of energy consumption is related to volume rates of 1.6 and 0.1 m³/s. At the inlet air volume flow rate of 1.6 m³/s, the highest drying rate of the samples is observed against the lowest amount of energy consumption. Therefore, it can be concluded that the control of inlet air volume flow rate is essential in the second step of drying of epoxy-based coating powder.

4. Conclusion

In this study, the effect of inlet air temperature and volume flow rate was investigated on the drying rate of epoxy-based coating powder in a fluidized bed dryer system. The effect of drying rate on the energy consumption of system was studied to optimize the drying operational parameters. An increase in the inlet air temperature and volume flow rate led to an increase in the drying rate of the samples. The drying rate of samples increased from 1.0 to 1.4 m³/s, and then decreased from 1.4 to 1.6 m³/s. An increase in the inlet air temperature led to an increase the energy consumption of the system. In contrast, an increase in the inlet air flow rate led to a decrease in the required energy of the system to reduce the moisture content of the samples. Therefore, a control on the inlet air temperature and volume flow rate is more effective in the second step of drying of epoxy-based coating powder than the first, and third steps. The energy consumption of the system at high inlet air temperature and low volume flow rate is attributed

to the high loss of thermal energy in the fluidized bed dryer system. The results can be effective in achieving the optimal parameters for drying process to achieve a standard value ($\leq 2\%$) by consuming the minimum heating energy and the maximum drying rate of epoxy-based coating powder.

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Biography



Alireza Bahramian currently works at the chemical engineering, Hamedan University of Technology. Alireza does research in chemical engineering, chemical kinetics and reactions. Their current project is 'Molecular Dynamic Simulation of Nanomaterials', and water treatment method by ultrafiltration process. His research area are nanotechnology, catalysis, chemical kinetics and simulation of energy processes, fluidization, CFD-DEM simulation of fluidized bed systems, drying and crystallization and chemical engineering topics.



Alireza Zafari currently study in MSc student at chemical engineering in Hamedan University of Technology. Alireza does research in chemical engineering, chemical kinetics and reactions. Their current project is on oil refinery in the South Pars of Iran.



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